# REASSESSMENT OF THE RISK OF FOLIAR INJURY FROM OZONE ON VEGETATION IN PARKS EXPERIENCING INCREASES IN LEVELS OF EXPOSURE

## Objective

The original assessment of the risk of foliar ozone injury on vegetation for parks in the 32 Vital Signs Networks was conducted in 2004 and used ozone exposure and soil moisture data for 1995 through 1999. This reassessment uses monitoring data for ozone from 2000 through 2004 to update the risk assessments for selected parks. Together the two assessments provide insight to the changes in ozone exposure over a ten-year period, and examine how the changes may have altered the risk of ozone injury to plants.

The reassessment of risk was conducted for Craters of the Moon National Historic Park, Death Valley National Park, Grand Canyon National Park, Great Basin National Park, Mesa Verde National Park, Rocky Mountain National Park, Sequoia and Kings Canyon National Park, and Yellowstone National Park. These parks were selected because it appeared they experienced increased levels of ozone exposure since the initial assessment. This document contains the reassessment for Rocky Mountain National Park. Other reassessments can be accessed from the appropriate park's AQRV page on ARIS at http://www2.nature.nps.gov/air/Permits/ARIS/.

## Risk Assessment Methodology

The risk assessment is based on a triad model that holds that the response of a plant to ozone is the result of the interaction of the plant, the level of exposure and the exposure environment. While interactions among the three variables determine the response, the state of any one of them can serve to accentuate or preclude the production of foliar injury. The response is greatest when all three variables and their interactions are optimized relative to the conditions that foster injury. The optimized states are: the species of plants are highly sensitive to ozone, the exposure levels of ozone significantly exceed the thresholds for foliar injury, and the environmental conditions foster gas exchange and the uptake of ozone by plants.

To conduct a risk assessment for a specific site, information was obtained on the ozone-sensitive plant species found there, the levels of ozone exposure that occur over a number of years, and, since soil moisture is a critical variable controlling gas exchange, the levels of soil moisture that exist during the periods of ozone exposure. The information was evaluated to determine the degree to which the levels of ozone exposure and soil moisture conditions integrate to create an environment that leads to the production of foliar injury on sensitive species at the site.

## Ozone-Sensitive Plant Species

In 2003, a workshop was convened by the National Park Service to review the ozone research literature and apply the field experience of the attendees to develop a

comprehensive list of ozone-sensitive plant species for the eastern and western United States. Because of the emphasis of previous field studies and research, information on the ozone-sensitivity of tropical, arctic and rare species is limited. The workshop identified both sensitive and bioindicator species for ozone, and published its determinations in a National Park Service Report (U.S. National Park Service 2003). An ozone bioindicator species is one whose high level of sensitivity and characteristic pattern of foliar injury allow it to be confidently used to ascertain the occurrence of injurious levels of ozone exposure in the field. With regard to the Triad model, a bioindicator species integrates the effects of exposure and environment while optimizing plant sensitivity. A bioindicator serves as an early-warning agent for the plant community with respect to the potential impacts of ozone. Ozone-sensitive and bioindicator plant species at each site were identified by comparing the site's floral list from NPSpecies with the list of sensitive species developed at the workshop.

**Levels of Ozone Exposure**

Ozone exposure data for each site were obtained either from on-site monitoring or by kriging. Both monitored and kriged data have limitations. Ozone monitoring was conducted at relatively few sites, but provides the most accurate assessment of ozone exposure. However, data from a single monitor may not accurately represent exposures throughout a large park, or a park with significant elevation differences. For sites without monitoring, ozone data were statistically estimated using a technique known as kriging. This technique uses ozone data from near-by monitoring sites to estimate data for the point of interest. Most of the sites in the risk assessment have kriged data. The accuracy of the kriged data depends on the number of near-by monitoring sites, their distance and their spatial arrangement. The accuracy with which the kriged data represents the actual exposure conditions is likely to vary among the sites.

All ozone data, both monitored and kriged, were analyzed by the Air Resources Division of the National Park Service to produce annual indices of exposure for each site. Since the ozone research community has not completely accepted one index of exposure as fully characterizing the threshold for foliar injury to vegetation, the assessment employed three indices to assure a comprehensive approach was taken in the assessment.

One index is the Sum06 and its attendant thresholds for injury (Heck and Cowling 1997). This index is comprised of the 90-day maximum sum of the 0800 through 1959 hourly concentrations of ozone $\geq$ 60 ppb (0.60 ppm). The index is calculated over running 90-day periods and the maximum sum can occur over any period of the year, although the chemistry of ozone generation usually results in it occurring over the summer months. For risk assessment purposes, it is also necessary to know the three-month period over which each year's maximum index occurs.

Another index is the W126 and its associated thresholds (Lefohn et al. 1997). The W126 index is the weighted sum of the 24 one-hour ozone concentrations daily from April through October, and the number of hours of exposure to concentrations $\geq$ 100 ppb (0.10 ppm) during that period. The W126 index uses a sigmoidal weighting function in

producing the sum: the lower concentrations are given less weight than are the higher concentrations since the higher exposures play a greater role in producing injury. The significance of the higher concentrations is also reflected in the requirement that there be a specified minimum number of hours of exposure to concentrations ≥ 100 ppb. Thus, the W126 index has two criteria that must be realized to satisfy its thresholds: a minimum sum of weighted concentrations and a minimum number of hours ≥ 100 ppb.

The last indicator of ozone exposure, designated N-value, consists of the numbers of hours of exposure each year that exceeded 60, 80 and 100 ppb. While there are no formal thresholds associated with these values, they provide insight to the distribution of exposures among these concentrations, and to the numbers of hours at and above 80 and 100 ppb, levels of exposure that are associated with the production of foliar injury.

**Soil Moisture Status**

Although gas exchange in plants is influenced by many environmental variables, soil moisture status is a critical factor since stomatal closure during periods of low soil moisture can severely limit gas exchange. Since site-specific soil moisture data are not available for the sites, the USDA's Palmer Z Index was selected to represent soil moisture conditions. The Palmer Z Index is a measure of the short-term departure of soil moisture from the long-term mean for the area. Consequently, the index automatically takes into account the diversity in precipitation among the parks, and emphasizes the difference that exists between the monthly soil moisture norm for the site and its actual state. The index is calculated monthly for up to ten regions in each of the 48 contiguous states, and measures drought on a scale from 0.0 to –4.0, a range representing normal to severe conditions. The regions are considered to be relatively homogeneous by USDA, but contain a diversity of soil, elevation and site variables that influence the soil moisture conditions at any specific location. The Palmer Z Index is not site specific and may not fully represent the soil moisture conditions at a park during a specific month.

The objective of this aspect of the risk assessment was to determine whether there is a consistent relationship between the level of ozone exposure and soil moisture status for the site by using the five years of data available. Atmospheric conditions that foster the production of ozone, such as clear sky, high UV levels and higher temperatures, are ones associated with the presence of few clouds and reduced precipitation. Consequently, years with high levels of atmospheric ozone may also experience low levels of soil moisture. This inverse relationship can constrain the uptake of ozone by plants in years with high levels of ozone and significantly reduce the likelihood that foliar injury will be produced. Knowing whether this relationship exists at a site is essential in determining whether certain levels of ozone exposure pose a risk to vegetation.

Palmer Z data were obtained from the USDA web site and tabulated for the three-month period over which the Sum06 exposure indices were compiled, and for the May to October period associated with the W126 exposure indices. Visual analysis of the exposure and soil moisture data was undertaken to determine whether there was an association between the two factors at each site.

**Site-Specific Assessment**

After information on the presence of sensitive species, levels of ozone exposure and relationships between exposure and soil moisture was compiled, it was synthesized into an assessment of risk of foliar injury for the site. Risk was classified as high, medium or low. Most sites had ozone-sensitive species on them and some of species were bioindicators that could be used in field surveys for ozone injury. If a site did not have any sensitive species, the risk assessment was completed and considered to be potential until sensitive species are identified.

The Sum06 and W126 exposure indices were examined to determine whether they exceeded their respective thresholds for injury, and the frequency with which the thresholds were exceeded over the five-year assessment period. The N-value data were examined to assess the distribution of exposures in a given year, and the consistency of exposure over the five years.

Evaluation of the relationship between ozone exposure and soil moisture might indicate they are inversely related, or they are not related and months of drought occur independent of the level of ozone exposure. At a site where exposure and drought are inversely related, the uptake of ozone is constrained by drought stress in the highest exposure years. In this instance, the risk of foliar ozone injury is likely greatest in years with lower levels of exposure that still exceed the injury thresholds and with soil moisture conditions that are more favorable for the uptake of ozone. In these cases, the greatest risk of foliar injury does not necessarily occur in the year with the highest level of ozone exposure. At sites where exposure and soil moisture are not related, the risk of foliar injury in a given year is a function of the random co-occurrence of high exposure and favorable moisture conditions.

The risk of foliar ozone injury at a site was determined by analyzing the plant, exposure and moisture data. The process was not quantitative, but based upon three primary evaluations: the extent and consistency by which the ozone injury thresholds were exceeded by the Sum06 and W126 exposure indices, the nature of the relationship between exposure and soil moisture, and the extent to which soil moisture conditions constrained the uptake of ozone in high exposure years. The evaluation of these factors and the assessment of their interactions with ozone-sensitive plant species is consistent with the triad model of risk assessment, and comprises the framework for determining whether the risk of foliar ozone injury was high, moderate or low at each site. The accuracy of a site's risk assessment is dependent upon the quality of the plant list, the accuracy of the ozone exposure data and the degree to which the regional soil moisture data represent conditions at the site.

Sites receiving a risk rating of high have a probability of experiencing foliar injury in most years, while those rated low are not likely to experience injury in any year. A rating of moderate was assigned to sites where analysis indicated injury was likely to occur at some point in the five-year period, but the chance of injury occurring consistently was low. In other words, foliar injury will probably occur at sites rated moderate, but it is not

anticipated it will occur regularly or frequently. Sites rated moderate are likely to experience a wide temporal variation in the occurrence of injury, and over a period of time may experience injury for one or more years while also experiencing several years without injury.

**Literature Cited**

Heck, W.W. and E.B. Cowling. 1997. The Need for a Long-term Cumulative Secondary Ozone Standard - An Ecological Perspective. Environmental Management. January

Lefohn, AS, W Jackson, D. Shadwick, and HP Knudsen. 1997. Effect of surface ozone exposures on vegetation grown in the Southern Appalachian Mountains: identification of possible areas of concern. Atmospheric Environment 31(11):1695-1708.

U.S. National Park Service. 2003. Ozone Sensitive Plant Species on National Park Service and US Fish and Wildlife Service Lands. NPS D1522. Natural Resource Report NPS/NRARD/NRR-2003/01. Air Resources Division. Denver, CO. 21 pp. (Available at www2.nature.nps.gov/ard/pubs/index.htm)

# ROCKY MOUNTAIN NATIONAL PARK
# (ROMO)

## Plant Species Sensitive to Ozone

| *Latin Name* | *Common Name* | *Family* |
|---|---|---|
| Amelanchier alnifolia | Saskatoon serviceberry | Rosaceae |
| Apocynum androsaemifolium | Spreading dogbane | Apocynaceae |
| Populus tremuloides | Quaking aspen | Salicaceae |
| Rudbeckia laciniata | Cut-leaf coneflower | Asteraceae |
| Salix scouleriana | Scouler's willow | Saliaceae |

## Representative Ozone Injury Thresholds

Sum06 -- The running 90-day maximum sum of the 0800-2000 hourly ozone concentrations of ozone equal to or greater than 0.06 ppm. Index is in cumulative ppm-hr.

| | | |
|---|---|---|
| Natural Ecosystems | 8 - 12 ppm-hr | (foliar injury) |
| Tree Seedlings | 10 - 16 ppm-hr | (1-2% reduction in growth) |
| Crops | 15 - 20 ppm-hr | (10% reduction in 25-35% of crops) |

W126 -- A cumulative index of exposure that uses a sigmoidal weighting function to give added significance to higher concentrations of ozone while retaining and giving less weight to mid and lower concentrations. The number of hours over 100 ppb (N100) is also considered in assessing the possible impact of the exposure. The W126 index is in cumulative ppm-hr.

| | W126 | N100 |
|---|---|---|
| Highly Sensitive Species | 5.9 ppm-hr | 6 |
| Moderately Sensitive Species | 23.8 ppm-hr | 51 |
| Low Sensitivity | 66.6 ppm-hr | 135 |

## Ozone Exposure Data

Ambient concentrations of ozone monitored on-site were analyzed to generate annual exposure values. The exposure values include the Sum06 and W126 exposure indices in ppm-hr and the annual number of hours above 60, 80 and 100 ppb (N60, N80 and N100, respectively).

| Ozone air quality data for ROMO | | | | | |
|---|---|---|---|---|---|
| | 1995 | 1996 | 1997 | 1998 | 1999 |
| Sum06 | 15 | 24 | 10 | 28 | 13 |
| W126 | 29.1 | 37.0 | 28.7 | 47.0 | 6.9 |
| N60 | 331 | 566 | 388 | 843 | 431 |
| N80 | 21 | 21 | 8 | 36 | 15 |
| N100 | 0 | 0 | 0 | 2 | 1 |

| Ozone air quality data for ROMO | | | | | |
|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2004 |
| Sum06 | 38 | 9 | 49 | 43 | 22 |
| W126 | 50.9 | 22.8 | 71.4 | 67.4 | 43.4 |
| N60 | 931 | 306 | 1394 | 1332 | 757 |
| N80 | 52 | 7 | 133 | 101 | 9 |
| N100 | 2 | 0 | 4 | 4 | 0 |

**Soil Moisture Status**

The uptake of ambient ozone by a plant is highly dependent upon the environmental conditions under which the exposure takes place, and the level of soil moisture is an important environmental variable controlling the process. Understanding the soil moisture status can provide insight to how effective an exposure may be in leading to foliar injury. The Palmer Z Index was selected to indicate soil moisture status since it represents the short-term departure of soil moisture from the average for each month for the site. The objectives of the assessment were to examine the relationship between high annual levels of ozone and soil moisture status, and to consider the impact reduced soil moisture status would have on the effectiveness of exposure.

The Palmer Z Index is calculated for up to 10 regions within a state and therefore is not a site-specific index. Without site-specific data, ozone/soil moisture relationships can only be estimated. Site-specific criteria such as aspect, elevation, and soil type can alter soil moisture conditions such that they depart from those determined for the region. However, in lieu of site-specific data, the Palmer Z Index is the best estimate of short-term soil moisture status and its change throughout the growing season.

Palmer Z data were compiled for the site for both the three months used to calculate the Sum06 index and for the April through October period for the W126 index for 1995 through 1999. The Palmer Z index ranges from approximately +4.0 (extreme wetness) to –4.0 (extreme drought) with ±0.9 representing normal soil moisture.

Rocky Mountain National Park sits astride two of the state divisions used by the National Weather Service Prediction Center in its calculation of Palmer Z data. With respect to the park, Zone 2 covers the area from the Continental Divide west and Zone 4 covers the area east of the Continental Divide. Most of the park resides in Zone 2. For the period 1995 through 1999, soil moisture conditions in the two zones were similar, and data from Zone 2 were used to characterize soil moisture conditions in the park. For the period 2000 through 2004, soil moisture indices in the zones were somewhat different, and data for both zones are presented below. Since ozone exposures in the park are likely the result of upslope movement from the Denver Metropolitan area, data from Zone 4 are emphasized in the assessment.

Soil moisture status for the Sum06 index period.

| Palmer Z Index data for 3-month Sum06 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 1995 | 1996 | 1997 | 1998 | 1999 |
| Month 1 | 5.31 | 0.86 | 3.50 | -0.85 | 1.58 |
| Month 2 | 1.79 | 1.08 | -0.65 | 0.67 | 1.70 |
| Month 3 | 0.89 | 0.32 | 3.47 | 5.84 | 3.00 |

Soil moisture status for the April through October period for the W126 index.

| Palmer Z Index data for the 7-month W126 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 1995 | 1996 | 1997 | 1998 | 1999 |
| April | 3.79 | -0.69 | 3.50 | 2.92 | 7.48 |
| May | 7.46 | 1.38 | -0.65 | -0.85 | 1.58 |
| June | 5.31 | 0.86 | 3.47 | 0.67 | 1.70 |
| July | 1.79 | 1.08 | 3.35 | 5.84 | 3.00 |
| August | 0.89 | 0.32 | 6.34 | 1.81 | 5.30 |
| September | 3.10 | 3.91 | 2.47 | -0.80 | 2.21 |
| October | -0.26 | -0.55 | 3.49 | 2.04 | -0.11 |

WEST OF THE CONTINENTAL DIVIDE: 2000 - 2004

Soil moisture status for the Sum06 index period.

| Palmer Z Index data for 3-month Sum06 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2004 |
| Month 1 | -1.86 | -1.68 | -5.65 | -1.14 | 1.54 |
| Month 2 | -3.08 | 0.48 | -4.80 | -3.43 | -2.54 |
| Month 3 | -0.45 | -2.11 | -2.46 | -0.88 | -1.27 |

Soil moisture status for the April through October period for the W126 index.

| Palmer Z Index data for the 7-month W126 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2004 |
| April | -2.64 | -1.46 | -4.20 | -1.77 | 1.54 |
| May | -1.71 | -1.12 | -4.29 | -0.60 | -2.54 |
| June | -1.86 | -2.64 | -5.65 | -1.14 | -1.27 |
| July | -3.08 | -1.68 | -4.80 | -3.43 | -1.38 |
| August | -0.45 | 0.48 | -2.46 | -0.88 | -2.00 |
| September | -0.60 | -2.11 | 2.10 | 0.86 | 3.58 |
| October | -0.23 | -1.72 | 0.78 | -3.01 | 0.59 |

EAST OF THE CONTINENTAL DIVIDE: 2000 - 2004

Soil moisture status for the Sum06 index period**.**

| Palmer Z Index data for 3-month Sum06 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2004 |
| Month 1 | -2.28 | 0.38 | -3.81 | 1.87 | 1.72 |
| Month 2 | -1.92 | 0.27 | -4.45 | -1.51 | -2.81 |
| Month 3 | 0.12 | -0.13 | -1.89 | 1.33 | 2.00 |

Soil moisture status for the April through October period for the W126 index.

| Palmer Z Index data for the 7-month W126 period at ROMO | | | | | |
|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2004 |
| April | -1.08 | 0.03 | -4.03 | 0.44 | 1.72 |
| May | -2.35 | 1.25 | -2.72 | -0.91 | -2.81 |
| June | -2.28 | -1.63 | -3.81 | 1.87 | 2.00 |
| July | -1.92 | 0.38 | -4.45 | -1.51 | 2.22 |
| August | 0.12 | 0.27 | -1.89 | 1.33 | 3.20 |
| September | 0.89 | -0.13 | 0.38 | -0.81 | 1.65 |
| October | -0.77 | -1.50 | 1.32 | -2.22 | 1.05 |

**Risk Analysis**

- There are a few ozone-sensitive species at the site, some of which are bioindicators for ozone.

**1995-1999**

- The Sum06 index exceeds the threshold for injury to vegetation. While the W126 accumulative value is above the threshold, the N100 count is below the required number and thus the criteria for injury are not satisfied.

- The N-values for the site show concentrations frequently exceeded 60 ppb and exceeded 80 ppb for a few hours each year. No year had more than two hours in which the concentration exceeded 100 ppb, and three years had no hours at this level. These levels of exposure are not likely to injure vegetation.

- During the five-year assessment period, soil moisture levels were normal to high and favored the uptake of ozone. Since there were no months of drought, it is not possible to determine whether a relationship exists between the level of soil moisture and either the 90-day cumulative Sum06 or the seasonal W126 index of exposure.

**2000-2004**

- The Sum06 index exceeds the threshold for injury to vegetation. In some years the threshold is exceeded by a considerable margin. While the W126 accumulative value is above the threshold, the N100 count is below the required number and thus the criteria for injury are not satisfied.

- The N-values for the site show concentrations frequently exceeded 60 ppb and often exceeded 80 ppb in some years. No year had more than four hours in which the concentration exceeded 100 ppb, and there were some years in which 100 ppb was not reached. These levels of exposure may possibly injure vegetation.

- West of the Continental Divide, soil moisture levels during the 90-day Sum06 and the seasonal W126 accumulation periods appear to be unrelated to the levels of ozone exposure. However, the numbers of months and levels of drought experienced each year would significantly reduce the uptake of ozone by plants. For the Sum06 index, all years experienced at least two months of mild to severe drought during the 90-day period, while for the W126 index there were four to six months of mild to severe drought during the seven-month accumulation period each year. East of the Continental Divide, soil moisture levels during the 90-day Sum06 and the seasonal W126 accumulation periods appear to be inversely related to ozone concentrations: when ozone is high, soil moisture is low. This relationship reduces the uptake of ozone and the effectiveness of the exposure in producing foliar injury. There are, however, some inconsistencies in the

relationship for both indices. The years with the three highest Sum06 ozone exposure values, 2002, 2003 and 2000 had respectively, three months of mild to severe drought, one month of mild drought, and two months of mild and moderate drought. The year with the second lowest level of exposure, 2004, experienced one month of moderate drought, while the year with the lowest exposure, 2001, had no drought. There was also an inverse relationship between W126 index of exposure and incidence of drought, with some inconsistency. The year with the highest exposure, 2002, had five months of mild to severe drought, while the second highest year, 2003, had two months of mild and moderate drought. The two years with next lower levels of exposure, 2000 and 2004, had four months of mild and moderate drought, and one month of moderate drought, respectively. The year with the lowest exposure, 2001, had two months of mild drought. Generally, the levels of drought experienced in the higher exposure years would reduce the uptake of ozone by plants and reduce the likelihood of foliar injury.

Levels of ozone exposure increased significantly over the 10-year assessment period at Rocky Mountain National Park, however the risk of foliar ozone injury is generally low. The threshold for injury is consistently satisfied for the Sum06 index. The cumulative value for the W126 index also consistently exceeds the threshold, however the associated criterion for the number of hours greater than 100ppb is not satisfied in any year. The N-values indicate that exposure to concentrations of ozone greater than 60 and 80 ppb increased significantly between the two assessment periods, and although exposures over 100 ppb are rare, they too increased. During the first 5-year assessment period, soil moisture levels were favorable for the uptake of ozone, but ambient levels of exposure were lower and foliar injury was not likely to be produced. Levels of exposure increased significantly in the second five-year assessment period, however the incidence of mild to severe drought also increased. The occurrence of low levels of soil moisture during periods of high ozone exposure greatly reduces the potential for foliar injury since the uptake of ozone by the plant is reduced. Extended meteorological conditions that foster the production of atmospheric ozone, such as intense sunlight and high temperatures, are also associated with reduced precipitation and greater evaporation of soil moisture all of which reduce gas exchange by plants. If there is a year in which this relationship becomes uncoupled and high levels of exposure occur under conditions of normal soil moisture or mild drought, the risk of foliar injury will increase.

It is worth noting that Palmer Z Index zones 2 and 4 are large and contain considerable diversity in elevation and ecology. It is not possible to determine whether the soil moisture levels calculated for the zones are necessarily representative of those in Rocky Mountain National Park. If during periods of elevated ozone exposure the soil moisture levels in the park are higher than those calculated for the zone, the risk of ozone injury could be greater in a given year.

The trends of increasing levels of exposure may create concerns in the future. While the interactive effects of low levels of soil moisture serve to constrain the uptake of ozone and reduce the potential for injury, the responses of western plant species to long-term exposure to elevated, but still relatively low, levels of ozone under varying degrees of

drought are not well understood.  Attention should continue to be paid to the levels of exposure in the park and the soil moisture conditions under which they occur.

If the level of risk increases in the future, a program to assess the incidence of foliar ozone injury on plants at the site could use one or more of the following bioindicator species: spreading dogbane, quaking aspen, cut-leaf coneflower, and Scouler's willow.